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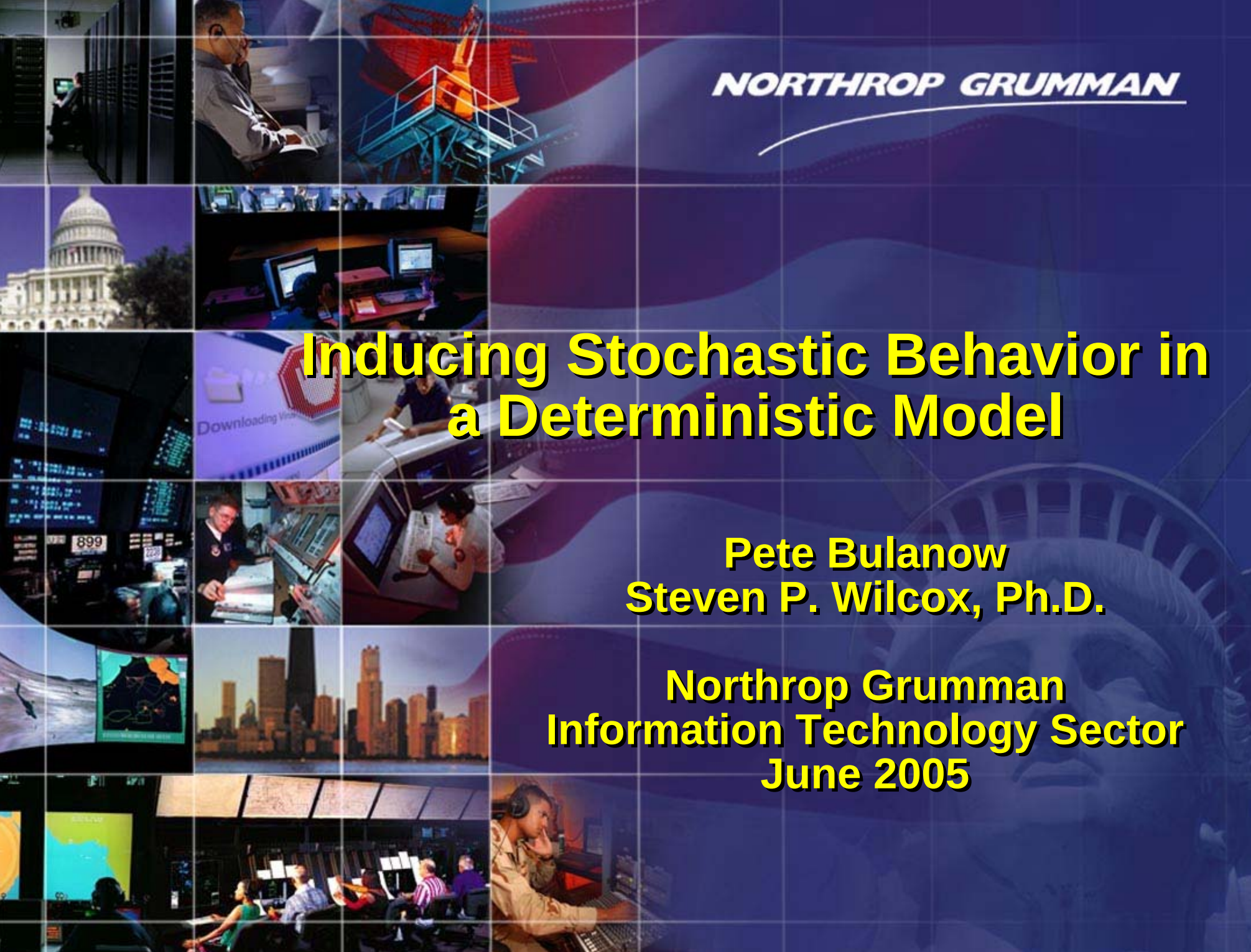

Inducing Stochastic Behavior in a Deterministic Model

Pete Bulanow
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Information Technology Sector
June 2005

Overview

- Background
  - Understanding the Value Added Analysis Process
- Challenges
  - Demand for quick-turnaround analysis
  - Non-monotonic relationships between parameters and VIC outcomes
  - Statistical analysis to support accurate decision making
- Our Answer
  - Induce stochastic variation in VIC runs through perturbation
  - Utilize statistical tests for comparisons of options
- Benefit
  - More accurate decisions about equipment trades using VIC as part of the Value-Added Analysis process

The Value Added Analysis Process

- Supporting the Center for Army Analysis (CAA)
- Uses the Vector-in-Commander (VIC) Corps-level combat simulation model
- Objective:
  - Estimate the incremental contribution of system trades to combat effectiveness
  - Perform a cost-benefit analysis to determine the actual 'value-added' of the systems of interest.
- Previous methodology was a typical DOE approach
- Now a perturbation methodology induces stochastic behavior in VIC

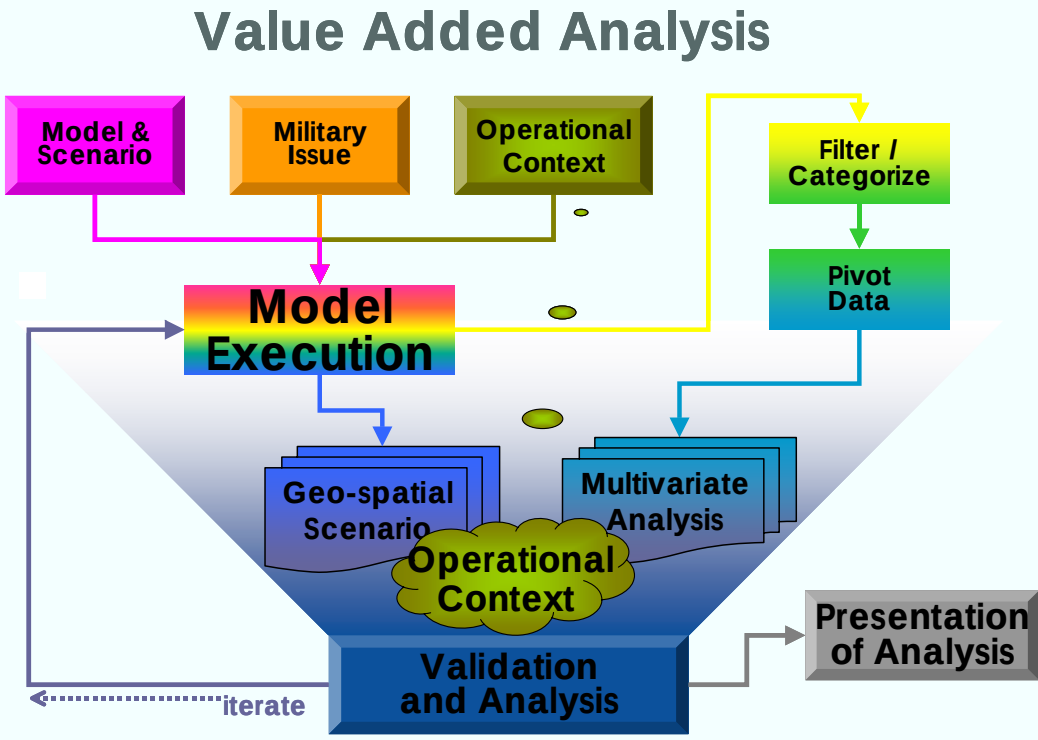


Figure 1. The VAA Process

The Force Exchange Ratio

- **Primary Measure of Effectiveness (MOE) in the VAA process**
- **Force Exchange Ratio (FER)**
  - **Ratio of relative losses**
  - **Used as a proxy for the win probability**
  - **Only high-value equipment losses are counted in our version**

$$FER = \frac{Losses_R / Strength_R}{Losses_B / Strength_B}$$

Legacy Methodology

- Comparing FERs using a Design of Experiments
- A typical DOE is to run a number of combinations of experimental settings
  - And then analyze the MOEs using analysis of variance
  - Differences in the means between treatments indicate possible differences in effectiveness
- Statistical efficiency is achieved at the cost of elaborate run setups.

Run	Sys1	Sys2	Sys3	Sys4	Sys5	Sys6	Sys7
1	1	1	1	1	1	1	1
2	1	1	1	-1	1	-1	-1
3	1	1	-1	1	-1	-1	-1
4	1	1	-1	-1	-1	1	1
5	1	-1	1	1	-1	-1	1
6	1	-1	1	-1	-1	1	-1
7	1	-1	-1	1	1	1	-1
8	1	-1	-1	-1	1	-1	1
9	-1	1	1	1	-1	1	-1
10	-1	1	1	-1	-1	-1	1
11	-1	1	-1	1	1	-1	1
12	-1	1	-1	-1	1	1	-1
13	-1	-1	1	1	1	-1	-1
14	-1	-1	1	-1	1	1	1
15	-1	-1	-1	1	-1	1	1
16	-1	-1	-1	-1	-1	-1	-1

DOEs aid in making statistical "decisions":

$FER(X_1 = 1) - FER(X_1 = -1) > 0$?

How big is the difference?
What is the confidence interval?

Two Paradigm Shifts

- VIC and complexity
  - Battle is a complex dynamical system
  - The results of battle are somewhat uncertain
    - Especially when the foes are close to evenly matched
  - VIC battles are a realization of a complex dynamical system
    - Sensitivity to parameters and initial conditions should be expected

- Embrace complexity
  - In support of quick turnaround analysis
  - Using the statistical perspective

Inducing the Expected Variability

- **Statistical methods require variability and replication.**
- **Key Requirements for inducing stochastic behavior consistent with accurate analysis:**
  - **Must not alter any performance data (Bailey, 2001)**
  - **Must affect many battlefield operating systems (Bailey, 2001)**
  - **Must continuously perturb the run – not just the initial conditions (Bailey, 2001)**
  - **Retains the original scenario setup within the precision of combat operations**

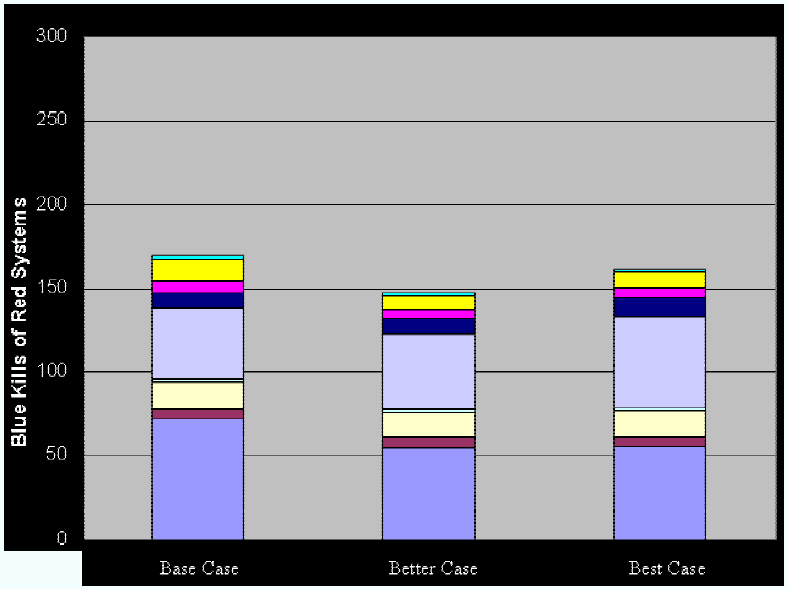
A Perturbation Methodology

- Our method perturbs several things a “small” amount
  - Unit locations and waypoints
  - Helo path points
  - Airborne sensor orbit points
- See Bulanow et al. (2004) for validation with respect to using the outputs in statistical models

The Difficulty with the Two-Run Comparison

- **Non-Monotonic effects have been observed in Deterministic Combat Models**
  - **Better settings do not necessarily mean a better FER**
- **Sensitivity to initial conditions and parameter values**
  - **Extensively noted in toy models of combat**
    - **The RAND model (Dewar, et al, 1991)**
  - **Also noted in VIC**
    - **Saeger & Hinch (2001)**
    - **Geoff Hawkins (1984) with VECTOR-2**
- **The DOE is a legacy solution to this problem, but a more responsive approach is required.**

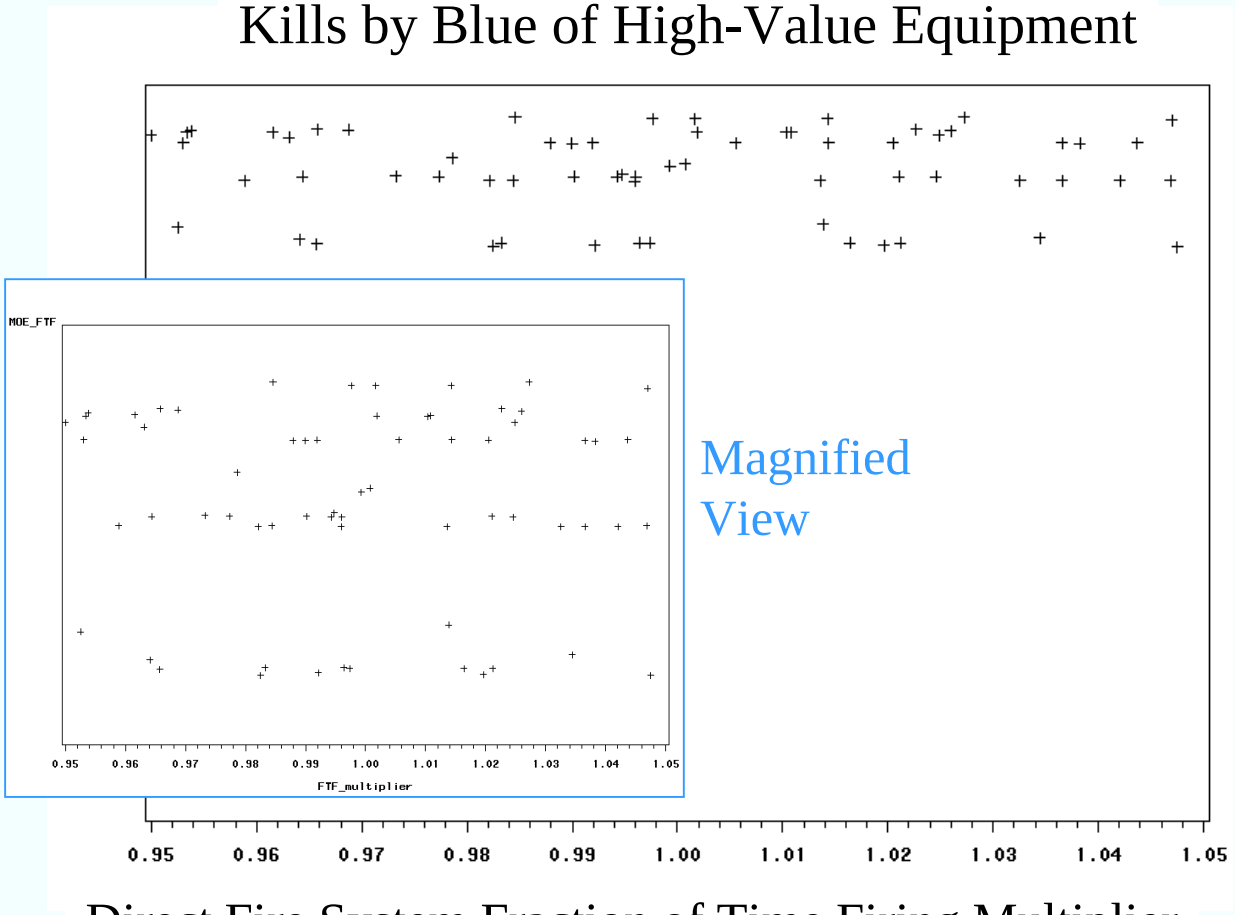
Kills of Selected Equipment by a Blue System of Interest



A three-way comparison of VIC results

Parametric Sensitivity in VIC

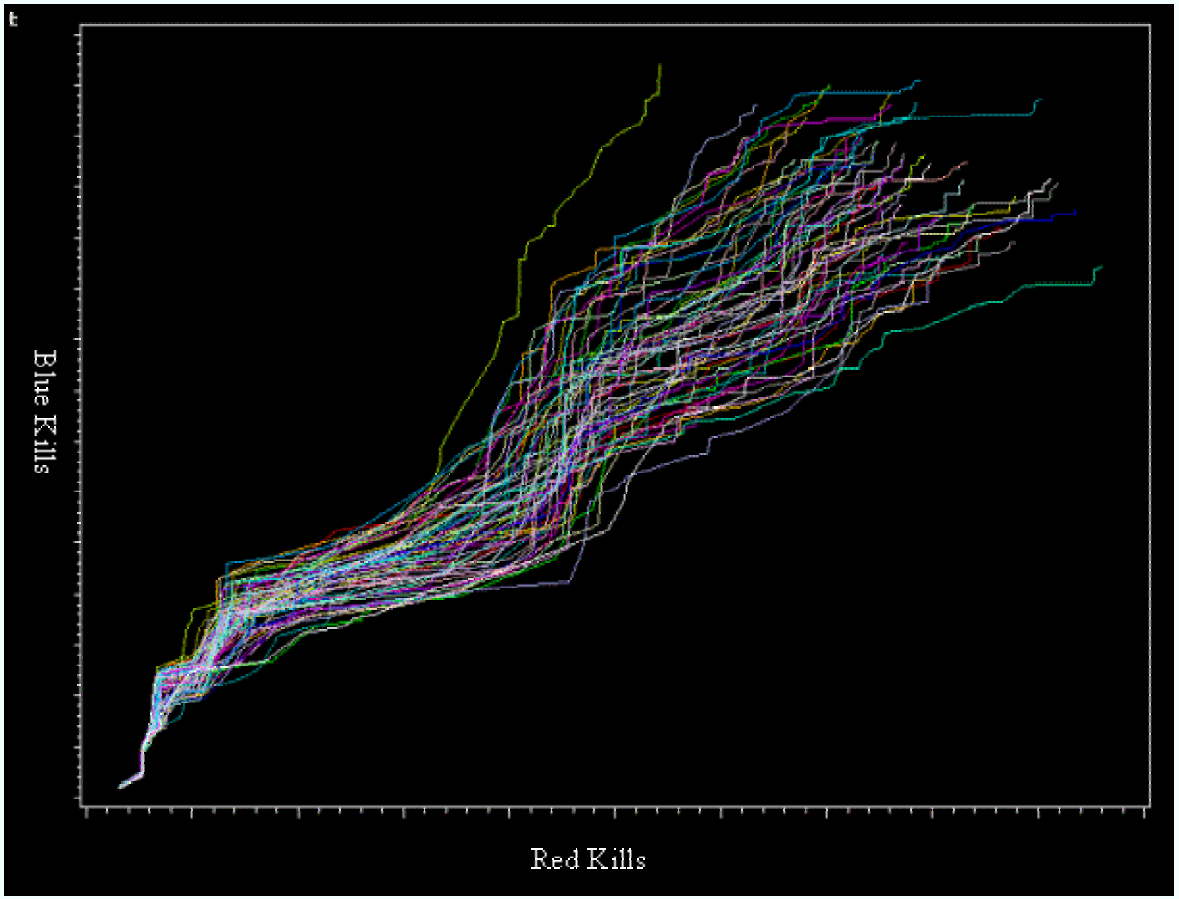
- A direct fire system (DF Sys) fraction of time firing (FTF) is multiplied by a number randomly selected from the interval (0.95, 1.05)
- Blue kills vary non-monotonically and significantly
- Any two runs selected from these might show a difference in the MOE
  - But is the difference statistically "significant"?



Inducing Variability Through Unit Locations

- **Perturbing ground unit locations and waypoints by ±10 meters produces very different pictures of the loss exchange ratio.**
- **Each color line represents the plot of Blue versus Red kills over the run for the original and 64 replications**
  - **X and Y scales include zero but are not the same**

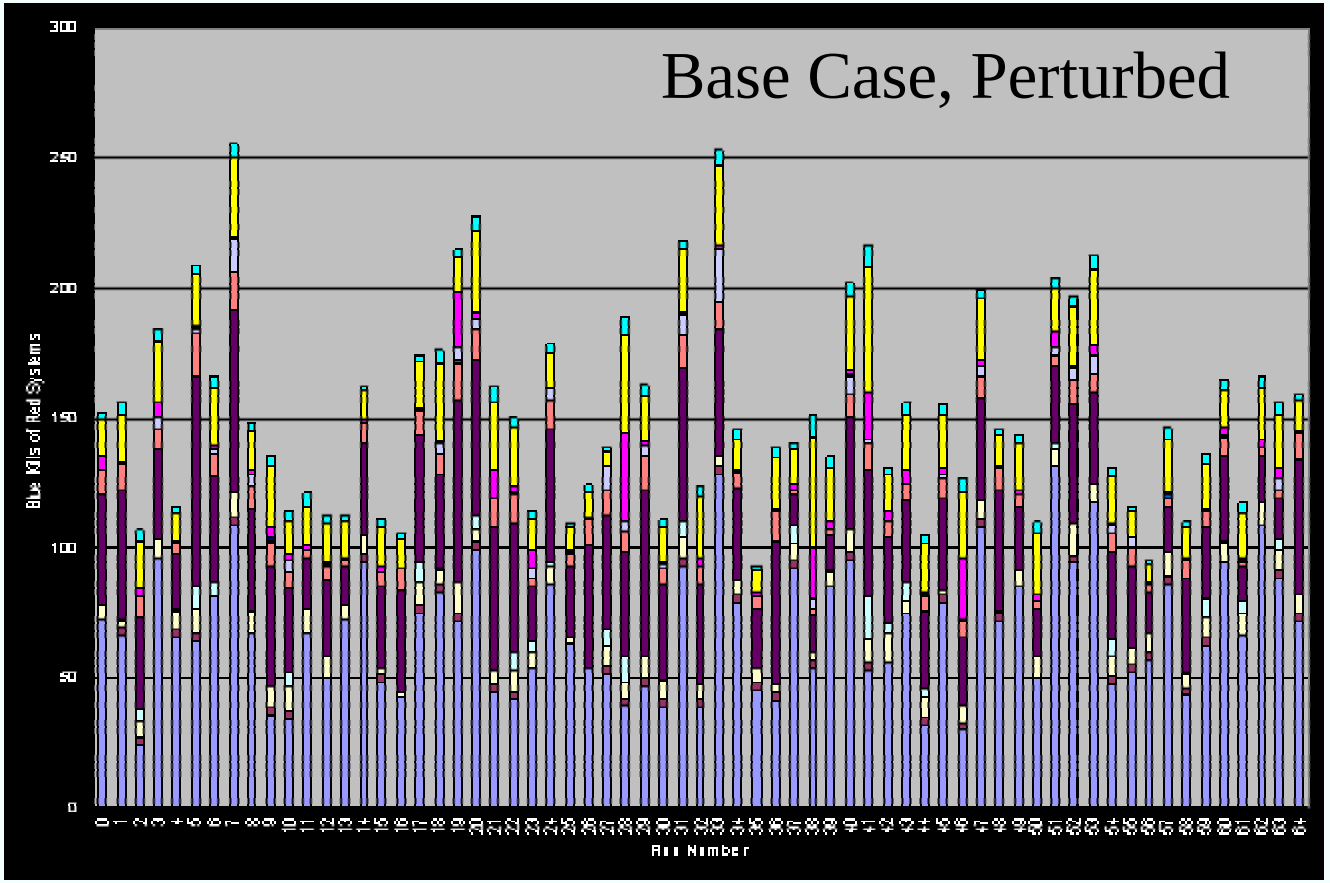
Kills by Blue and Red of High-Value Equipment



More on VIC's Stochastic Personality

- **Perturbing ground unit locations small amounts (a non-performance parameter) reveals a world of stochastic variability**
  - **Like what might happen in combat**
- **Statistical methods can characterize this variability for decision-making purposes**

Kills of Selected Equipment by the Blue System of Interest



Analysis Without DOE Matrices

- **Paired Comparisons can be performed without an elaborate DOE**

Perturbation Set	Base	Alternative A		Delta
1	B1	A1		A1 - B1
2	B2	A2		A2 - B2
3	B3	A3		A3 - B3
4	B4	A4		A3 - B4
5	B5	A5		A5 - B5
6	B6	A6		A6 - B6
...	...	...		...

- **We also perform multiple comparisons between numerous options**
- **More efficient for the analyst due to fewer run setups than with a DOE**
- **Has been employed in a variety of trade comparisons**

Effect of Replications on the Confidence Interval of Estimates

- Confidence intervals decrease as the inverse square root of sample size
- In actual applications, the standard deviation would be estimated

# Replications (and run time factor)	Confidence Interval (assuming a notional standard deviation, known in advance)
1	±32%
4	±16%
16	±8%
64	±4%
256	±2%

Conclusions and Way Forward

- Our perturbation analysis for VIC analysis aids in quick-turn analysis by:
  - Reducing run setups,
  - Simplifying design and analysis of experiments, and
  - Enabling statistical analysis with simple designs
- VIC run perturbation gives visibility to the complex system feature of combat
  - Even though VIC is deterministic
  - Thus providing an added window into the issue of outcome variability

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